Patent Application of

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for

POSITION SENSITIVE SOLID STATE DETECTOR WITH INTERNAL GAIN

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Statement Regarding Federally Sponsored Research and Development

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Background – Field of Invention

This invention describes methods of obtaining position of incidence information from solid state devices, such as avalanche photodiodes, without introducing any dead space to the detector's active area.

understood to be a contact of the device that has a negative potential relative to the anode when the device is forward biased.

This method offers a simple fabrication process, an easy readout approach even at very high effective pixel densities, and no dead space over the entire active area. This method also makes it easy to implement contact patterns that give a non-rectangular position readout as shown in Figures 3C and 4B.

Further objects and advantages of this invention will become apparent from a consideration of the drawings and ensuing description.

Drawing Figures

In the drawings, closely related figures have the same number but different suffixes.

Figure 1 shows the conceptual operation of a Position Sensitive APD.
Figure 2A shows a guard ring field spreading structure.
Figure 2B shows a planar bevel field spreading structure.
Figure ~~2B~~ 2C shows a beveled edge field spreading structure.
Figure 3A shows a corner cathode position sensitive readout approach for a Position Sensitive APD.
Figure 3B shows corner cathode contacts with arc termination lines to remove geometric distortion.
Figure 3C shows concentric ring contacts for measuring radial displacement.
Figure 3D shows arc contacts for mirror charge readout using patterned anodes.
Figure 4A shows a method for reading out a Position Sensitive APD using mirror charge.
Figure 4B shows a polar coordinate encoding anode pattern for use with a mirror charge readout.
Figure 4C shows a Cartesian coordinate encoding anode pattern for use with a mirror charge readout.
Figure 5 is a schematic diagram showing a method of operating a corner contact Position Sensitive APD for two dimensional imaging.
Figure 6A shows the results of using an optical pulser to evaluate the imaging performance of a two dimensional Position Sensitive APD with a corner contact readout as shown in Figure 3A.

Figure 6B shows the results of using an optical pulser to evaluate the imaging performance of a two dimensional Position Sensitive APD with an arc terminated corner contact readout as shown in Figure 3B.

Figure 7 details the spatial resolution achieved in the boxes shown in Figure 6A.

Figures 8A and 8B show~~s~~ the results of using a two dimensional Position Sensitive APD to detect 662 keV gamma rays from ^{137}Cs using proximity focused scintillator ~~CsI(Tl) and LSO~~ arrays with 2mm x 2mm elements.

Figure 9A shows a block diagram of the system used to measure timing resolution capabilities of the Position Sensitive APD in gamma ray detection applications

Figure 9B shows the ^{22}Na spectra obtained using LSO scintillator blocks coupled to the Photomultiplier tube (PMT) of the system in Figure 9A.

Figure 9C shows the ^{22}Na spectra obtained using LSO scintillator blocks coupled to the Position Sensitive APD (PSAPD) of the system in Figure 9A.

Figure 9D shows the measured timing resolution of the Position Sensitive APD with the PMT for detecting coincidence of gamma rays from ^{22}Na using in LSO scintillator blocks, using the system shown in Figure 9A.

Figures 10A and 10B show~~s~~ the rise time for the signal generated by an alpha source in a two dimensional Position Sensitive APD.

Figure 11 shows an embodiment where more than one continuous active area device is fabricated on a single substrate.

Summary

The present invention is a solid state detector that has internal gain and incorporates a special readout technique to determine the input position at which a detected signal originated without introducing any dead space to the active area of the device. In a preferred embodiment of the invention, the detector is a silicon avalanche photodiode that provides a two dimensional position sensitive readout for each event that is detected.

Description of Invention

Figure 1 shows a cross-section schematic of the conceptual operation of the invention. In a typical embodiment, a large area APD is fabricated in the usual way. It can be beneficial to the spatial resolution performance of the detector to minimize the thickness of the undepleted material on both sides of the depletion region **16**, especially on the input side of the detector **14**, in order to minimize the spread of minority carriers **12** produced by the input signal **60**. In a preferred embodiment, an n silicon substrate **18** is doped with p materials using a deep diffusion process. A field spreading structure **30** such as a guard ring **32** (Figure 2A), diffused bevel **34** (Figure 2B), or mechanical bevel **36** (Figure 2C) is incorporated into the semiconductor material to avoid edge breakdown under high reverse bias. Other field spreading structures are possible and are considered to be within the scope of this invention. Prior to applying a passivation layer to the cathode side of the device, a photomask is applied to mask off a contact pattern. The contact pattern can be somewhat arbitrary, but it is necessary that the cathode contacts **24** be sufficiently far from exposed features of the field spreading structure **30** so that arcing of the high voltage from the bulk material to the cathode contacts **24** will not occur. In a preferred embodiment, this distance is at least 30 mils. The location of the cathode contacts can be optimized based on the needs of the application for which the detector is being designed. In the case of two dimensional imaging over a continuous area, one method of optimization involves maximizing the distance between the contacts without enabling undesirable breakdown phenomenon between the cathode contacts **24** and the field spreading structure **30**; this provides a large central area of the device in which the need for distortion correction, whether built into the device or applied through signal processing, is minimized.

There are a variety of methods for generating the photomask and transferring it to a photoresist on the device. These methods are well known to people skilled in the art of semiconductor fabrication. In a preferred embodiment, a UV-activated photoresist is spun onto an APD substrate, and a contact imaging method is used to transfer the mask into the photoresist. The unmasked portion of the cathode is then etched back into the substrate far enough to produce a moderate resistivity (hundreds to thousands of ohms) between the masked contact areas. The optimum etch depth depends on the doping profile and desired operation characteristics of the device. The etch depth does not appear to be critical, as long as it gets close to the depletion region of the device **16** when it is under bias to enhance charge spreading 20 to the contacts **24**. In a preferred embodiment, the etch depth is on the

coordinates. In many applications, however, it may not be necessary to remove the pincushion distortion in order for the position sensing capabilities of the detector to be useful.

In another embodiment of this invention shown in Figure 4, the signal from the charge collected on a high resistivity cathode sheet **22** in an APD could be capacitively coupled to a patterned readout contact structure **44** separated from the cathode of said APD by an insulating dielectric layer **42**. In this configuration, a single cathode contact **46** suitably disposed around the perimeter of the cathode surface could be used, as shown in Figure 3D. It is important for the cathode contact **46** to be far enough from the field spreading structure **30** so that arcing of the high voltage from the bulk material to the cathode contacts will not occur. It is also important that the conductors **48a**, **48b**, **48c**~~, **48d**~~ be electrically isolated from each other and that they be sufficiently insulated from the high voltage of the bulk material to avoid arcing. Such readouts could offer greater flexibility in changing the position-sensitive readout geometry without altering the fabrication process for the semiconductor portion of the detector. Possible readout patterns include arrays of individual contacts, which would make it possible to achieve signals similar to what prior art pixilated devices offer in applications where pixel-style readouts are preferable.

Operation of Invention

In a preferred embodiment of this invention, a position sensitive avalanche photodiode **40** with four contacts **24a, 24b, 24c, 24d** for rectangular two-dimensional imaging is reverse biased as shown in Figure 5 using a high voltage power supply **58** and bias resistors **50a, 50b, 50c, 50d, 50e**. The signal from the anode contact **56** is connected to a charge sensitive preamplifier **54e** through a capacitor **52e**. The signal from the anode preamplifier **54e** is processed by a fast amplifier and discriminator to provide a timing pulse to trigger pulse height digitization and/or for coincidence determination. This same signal can also be processed by a slower pulse shaping amplifier to provide a total energy measurement for each detected event. The signals from the cathode contacts **24a, 24b, 24c, 24d** are connected to charge sensitive preamplifiers **54a, 54b, 54c, 54d** through capacitors **52a, 52b, 52c, 52d** and the resulting signals are processed by a slower amplifier. The signals from the four cathode contacts are processed by slower pulse shaping amplifiers, and an A/D board in a computer is used to digitize the pulse heights for each detected event. A computer

program, electronic circuit, or other means is then used to calculate an X-Y position for the detected event from the digitized pulse heights. The total energy for the detected event can also be calculated from the sum of the individual pulse heights.

In another embodiment of this invention involving a capacitively coupled position sensitive readout, the APD is reverse biased as shown in Figure 5 with only one cathode contact **46**, and signals from capacitive readout contacts **48a, 48b, 48c**~~, **48d**~~ in Figure 4C are connected to coupling capacitors 52e, **52a, 52b, 52c,** ~~**52d, 52e**~~.

Some examples of how to convert the signals from a position sensitive APD into Cartesian or polar coordinates are as follows. For the contact schemes in Figures 3A and 3B, the X and Y coordinates are determined from

$$X = \frac{(A+B)-(C+D)}{A+B+C+D}; \quad Y = \frac{(A+C)-(B+D)}{A+B+C+D}$$

In Figure 4B, the polar coordinates are determined from

$$r - r_0 = \frac{A}{A+B+C}; \quad \theta = \frac{2\pi B}{B+C}$$

In Figure 4C, the X and Y coordinates are determined from

$$X = \frac{2A}{A+B+C}; \quad Y = \frac{2B}{A+B+C}$$

In the equations above the values *A, B, C, D* are taken to be the peak pulse heights of the signals from pulse shaping amplifiers connected to the charge sensitive preamplifiers **54a, 54b, 54c, 54d** respectively. An important aspect of the present invention is that by including bias resistor **50e**, the anode signal from charge sensitive preamplifier **54e** corresponds to the total energy of radiation incident at any point within the active area of the detector. Furthermore, when the incident radiation is pulsed, it is possible to determine time of incidence from the same signal, for example by using a